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# Impact of watercore on gas permeance and incidence of internal disorders in 'Fuji' apples

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**Abstract**

The impacts of watercore on incidence of internal disorders and other physiological characteristics of 'Fuji' apples (*Malus domestica* Borkh) were determined following short-term exposure at 20 °C in 20 kPa $CO_2$ (high $pCO_2$) or long-term storage at 0.5 °C in 0.5 kPa $O_2 + 0.05$ kPa $CO_2$ (low $pCO_2$) or 1.5 kPa $O_2 + 3$ kPa $CO_2$ (medium $pCO_2$). $CO_2$-injury (brown-heart) occurred in apples exposed to high $pCO_2$ or medium $pCO_2$, but no internal disorders were observed in fruit held at 20 °C in air or 4 months at 0.5 °C in low $pCO_2$, regardless of watercore severity at harvest. Depending on harvest date and orchard, the severity of $CO_2$-injury was significantly correlated with watercore severity. Watercored tissue has a lower intercellular air space volume, reduced permeance to gas diffusion and increased internal $pCO_2$. Accumulation of ethanol and acetaldehyde occurred in watercored 'Fuji' apples even under ambient (21 kPa $O_2$) conditions and this accumulation increased with watercore severity regardless of storage environment. 

*Keywords:* Watercore; Gas exchange; Carbon dioxide injury

## 1. Introduction

Increases in watercore incidence and severity often occur prior to harvest of 'Fuji' apple fruit (Fukuda, 1984a). Watercored apples are characterized by a flooding of intercellular spaces, higher sorbitol and sucrose and lower glucose and fructose concentrations and the higher osmotic potential promotes water retention (Williams, 1966; Marlow and Loescher, 1984; Bowen and Watkins, 1997). Due to fluid accumulation in the intercellular space, stress concentrations of $O_2$ and or $CO_2$ may develop in the watercored tissue (Smagula et al., 1968). As gas exchange between the fruit and the surrounding atmosphere is critical to maintenance of aerobic respiration, the rate at which gases diffuse into and out of fruit is important in determining tolerance to low $O_2$ or high $CO_2$ environments.

The apple peel is the main barrier to gas exchange and oxygen gradient concentration across

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flesh tissue is normally small, due to a large intercellular space volume (Burg and Burg, 1965). However, in some apples, 'Braeburn' for example, the flesh exerts a significant resistance to $O_2$ diffusion resulting in a high $O_2$ gradient between tissues immediately beneath the peel and the center of fruit (Rajapakse et al., 1990). Calbo (1985) and Solomos (1987) also reported the existence of significant $CO_2$ gradients within apple fruit.

A number of disorders including flesh browning and brown watercore have been observed to occur with or following watercore development (Wilkinson and Fidler, 1973; Marlow and Loescher, 1984; Meheriuk et al., 1994). 'Delicious' apples with severe watercore tend to develop brown watercore, while fruit with medium to slight watercore are more likely to develop flesh browning (Fukuda, 1984b). Severe watercore present at harvest of 'Delicious' or 'Jonathan' apples can lead to accumulations of ethanol, acetaldehyde and ethyl acetate with subsequent internal breakdown of fruit during storage (Clijsters, 1965; Smagula et al., 1968). Despite the association of these factors, the relationship between watercore and subsequent development of internal disorders in 'Fuji' apples is unclear. 'Fuji' apples stored at 0 °C in air for 5 months have an increased incidence of core line browning with higher watercore intensity at harvest, but no correlation was found between watercore and inner-core browning (Fukuda, 1984a). Also, no correlation was observed between the severity of watercore at harvest and the incidence of internal breakdown after storage of 'Fuji' apples in controlled atmospheres (Park et al., 1997). 'Fuji' apples appear to be resistant to watercore-related internal browning if stored at 0 °C in air (Watkins et al., 1993), but susceptible to $CO_2$ injury when stored in CA at 1–5 kPa $CO_2$ (Park and Lee, 1991; Argenta et al., 1994).

The objective of this study was to examine the relationships between watercore severity, development of $CO_2$ injury, respiration, relative intercellular space volume, gas permeance, and concentrations of ethylene, ethanol and acetaldehyde in 'Fuji' apples.

## 2. Materials and methods

'Fuji' apples (*Malus domestica* Borkh) harvested from six commercial orchards near Wenatchee, WA, in 1997 were used in these studies. One day after harvest, fruit from orchards 1 and 2 were placed into 76 μm thick plastic bags, then air with or without $CO_2$ from compressed gas cylinders purged the bags at a flow rate of 6 l $h^{-1}$. Fruit was stored at 20 °C for 12 days in air or 10 kPa $O_2$ + 20 kPa $CO_2$ (balance $N_2$). $O_2$ and $CO_2$ concentrations were monitored by electrochemical and infrared gas analyzers (California Analytical Instruments, Orange, CA), respectively. For long-term storage, fruit from the same orchards was enclosed in 0.145 $m^3$ chambers at 0.5 °C and stored 4 months at 0.5 kPa $O_2$ + 0.05 kPa $CO_2$ (low $pCO_2$) or 1.5 kPa $O_2$ + 3 kPa $CO_2$ (medium $pCO_2$). The $O_2$ concentration was reduced beginning 36 h after harvest. Storage chamber atmospheres were established within 60 h after harvest and monitored at 90 min intervals (Techni-Systems, Chelan, WA.). Semi-static chamber atmospheres (purged only when atmosphere adjusted) were maintained with $N_2$ generated from a membrane system (Permea, St. Louis, MO), compressed air and $CO_2$. The low (0.05 kPa) $CO_2$ concentration was maintained by adding 0.1 kg of hydrated lime ($Ca(OH)_2$) per kg of fruit. For respiration analyses, individual fruit were enclosed in 3 l chambers maintained at 20 °C and supplied with compressed, ethylene-free air at 100 ml $min^{-1}$. The concentration of $CO_2$ in the effluent air was analyzed using a gas chromatograph (HP 5890; Hewlett–Packard, Avondale, PA) equipped with a methanizer (John T. Booker, Austin, TX), flame ionization detector and a 0.6 m, 2 mm i.d. stainless steel column packed with 80–100 mesh Porapak Q (Supelco, Bellefonte, PA). Oven, detector, methanizer and injection temperatures were 50, 200, 290 and 150 °C, respectively. Gas flows for $N_2$, $H_2$ and air were 70, 30 and 300 ml $min^{-1}$, respectively. $CO_2$ production was analyzed 36 and 24 h after removing fruit from short-term and long-term storage, respectively. Internal ethylene (IEC), acetaldehyde and ethanol concentrations of individual

fruit were measured in gas samples removed from the fruit core (Williams and Paterson, 1962). Analyses were conducted using a gas chromatograph (HP 5890; Agilent Technologies, Palo Alto, CA) equipped with a flame ionization detector and a 0.5 m, 3.2 mm i.d., glass column packed with 80–100 mesh Porapak Q (Supelco, Bellefonte, PA). Oven, detector, and injection temperatures were 90, 200 and 100 °C, respectively, and $N_2$, $H_2$, and air flows were 25, 25, and 300 ml $min^{-1}$, respectively. A standard gas mixture containing 8.7 mmol $m^{-3}$ ethanol and 9.1 mmol $m^{-3}$ acetaldehyde was prepared by injecting 5 μl of a standard solution containing 0.29 M ethanol and 0.28 M acetaldehyde in hexane into a 2 l gas dilution bottle earlier purged with helium. The solution was evaporated with stirring for 30 min. After the equilibration period, a 0.5 ml gas sample was withdrawn from the dilution bottle and analyzed by GC.

Gas permeance of whole apples or pulp cylinders was estimated using the ethane efflux method of Cameron and Yang (1982). Tissue cylinders ($20 \times 10$ mm) with the desired watercore severity were prepared from fruit cut in half through the equator. A cork borer was used to remove tissue on the core-line along the fruit axis. Whole fruit were enclosed in 3.84 l glass jars and 5 ml ethane was injected through a rubber septum in each lid to achieve a concentration of $1100 \pm 50$ μl $l^{-1}$. Apples were transferred to ethane-free glass jars after 16 h, then ethane concentration ($C$) was measured by removing 0.5 ml jar headspace with a syringe at 5 min intervals ($C^t_{out}$) over 30 min. Ethane flux was linear during this sampling period. The final ethane concentration ($C^{\alpha}_{out}$) was measured after 10 h. Ethane concentration in the headspace gas samples was measured using the same gas chromatograph used for ethylene measurements. Fruit volume was determined by measuring water displacment after fruit submersion. Resistance $R$ (s $cm^{-1}$) was calculated as, $R = A/k \times V_{in}$, where $k$ is the first-order efflux rate constant, $A$ is the surface area of the fruit ($cm^2$) calculated from fruit volume assuming a spherical shape, and $V_{in}$ is the volume inside the fruit accessible to ethane, estimated from $C^{\alpha}_{out}$ and the ratio between $V_{out}$ (volume of the jar) and $C^0_{in}$ (ethane concentration in the fruit at time zero). Permeance to ethane ($P'_{C_2H_6}$) was calculated as the reciprocal of $R$. $V_g$, relative intercellular air space volume, was expressed as percentage of $V_{in}$ in relation to the fruit volume. Experimental data for $V_g$ were corrected by 10% (Cameron, 1982) to account for the solubility of ethane in the tissue. The same methods were used to determine permeance of pulp cylinders except that cylinders were enclosed in 1 l jars, loaded with ethane for 5 h, $C$ was measured at 3 min intervals, and $C^{\alpha}_{out}$ measured after 5 h. All permeance experiments were conducted at 20 °C.

Watercore and $CO_2$-injury were scored visually after cutting fruit in half through the equator. Watercore severity was rated using a progressive scale from one (no watercore) to five (very severe watercore) similar to the method of Bowen and Watkins (1997) except that fruit rated 1 or 2 by Bowen and Watkins were rated as 2 in the present study. Watercored cylinders were scored as, 2–1% to 25%, 3–26% to 50%, 4–51% to 75%, and 5– > 75% of the tissue affected. The severity of $CO_2$-injury was scored as, (1) none, (2) 1–30%, (3) 31–60% or (4) 61–100% of cortex and pith tissues dark brown. Internal $CO_2$ partial pressure ($p^i_{CO_2}$) of apples harvested 192 DAFB from orchards 3 and 4 and 186 DAFB from orchards 5 and 6 was measured one day after harvest on gas samples removed from the fruit core (Williams and Paterson, 1962) using the method described earlier for respiration analysis.

Data analyses were performed using the Statistical Analysis System (SAS Institute, Inc., 1992, Cary, NC, USA). Treatment effects were analyzed by the ANOVA procedure and treatment mean separation was determined by Fischer's LSD ($P < 0.05$) or Duncan's multiple range tests. The relationship between watercore score at harvest and $p^i_{CO_2}$, and the relationship between internal ethylene concentration and $p^i_{CO_2}$ were examined by Kendall's tau-b and Pearson Product-moment correlation coefficients, respectively, combining data of two orchards from same harvest date. The same test was used to determine correlation between watercore score at harvest and brown-heart severity. Since watercore was rated after assessment of variables, the number of single-fruit replicates for each treatment (watercore score) ranged

from 3 to 16 for measurements of respiration, $P'_{C_2H_6}$ and $V_g$ and at least 3 (for long term-storage) or 18 (for short-term storage) single-fruit replicates were evaluated for incidence of disorders, ethylene, ethanol and AA concentrations. Four 6-cylinder replicates were used for measurements of $P'_{C_2H_6}$ and $V_g$ in pulp cylinders.

## 3. Results

Brown-heart, a typical symptom of $CO_2$-injury (Wilkinson and Fidler, 1973; Meheriuk et al., 1994), developed in apples held short- or long-term in high $CO_2$ (Table 1). No internal disorders occurred in fruit held at 20 °C in air or 4 months at 0.5 °C in 0.5 kPa $O_2$ + 0.05 kPa $CO_2$, regardless of watercore severity at harvest (data not presented). Severity of brown-heart was low and not correlated with watercore severity in fruit exposed to 20 kPa $CO_2$ for 3 d (Table 2). However, for fruit held 6–12 d in 20 kPa $CO_2$, the correlation between watercore and brown-heart severity was significant except for fruit harvested 173 DAFB from orchard 2. The highest correlations were after 9 days in 20 kPa $CO_2$. Similarly, watercore and $CO_2$-injury severity for fruit stored 4 months in 1.5 kPa $O_2$ + 3 kPa $CO_2$ were also correlated. In apples harvested 186 and 192 dafb, $p^i_{CO_2}$ varied from 0.3 kPa to approximately, 4.5 kPa depending on the watercore severity, orchard and maturity at harvest (Fig. 1). For fruit from an individual orchard, $p^i_{CO_2}$ was not usually correlated with watercore severity and IEC. However, for apples with severe watercore and high IEC from the same harvest date, $p^i_{CO_2}$ increased with watercore severity (Fig. 1).

In apples harvested 180 dafb, $P'_{C_2H_6}$ and $V_g$ decreased with increased severity of watercore (Fig. 2A and B). In fruit harvested earlier (165 DAFB), however, $P'_{C_2H_6}$ and $V_g$ of watercored and watercore-free apples were not statistically different. $P'_{C_2H_6}$ and $V_g$ of flesh cylinders decreased with increasing watercore severity (Fig. 2C) with the values in cylinders with severe (score = 5) watercore approximately, 7- and 2-fold lower, respectively, than in watercore-free cylinders. No differences in respiration rate were detected among fruit with different watercore ratings held 9 days at 20 °C in air (data not presented). However, fruit with high watercore ratings held 9 days after harvest at 20 °C in 10 kPa $O_2$ + 20 kPa $CO_2$ had higher respiration rates than watercore-free fruit (data not presented). IEC of fruit held 9 days at 20 °C in air tended to increase in fruit with low watercore scores (2–3) and to decrease with higher watercore ratings (Fig. 3). In fruit held 9 days at 20 °C under 10

Table 1
Severity of $CO_2$-injury in 'Fuji' apples as affected by watercore. Fruits harvested 173 DAFB or 188 DAFB, held 9 days at 20 °C in 10 kPa $O_2$+20 kPa $CO_2$ or stored for 4 months at 0.5 °C in 1.5 kPa $O_2$+3 kPa $CO_2$

| Watercore score | 9 days at 20 °C, 10 kPa $O_2$+20 kPa $CO_2$ | | | | 4 month at 0.5 °C, 1.5 kPa $O_2$+3kPa $CO_2$ | |
|---|---|---|---|---|---|---|
| | 173 DAFB | | 188 DAFB | | 188 DAFB | |
| | Orchard 1 | Orchard 2 | Orchard 1 | Orchard 2 | Orchard 1 | Orchard 2 |
| 1 | 2.1 b[a] | | | 1.3 b | 1.1 b | 1.0 b |
| 2 | 2.7 ab | 1.6 a | 2.7 b | 2.7 a | 1.5 b | 1.6 ab |
| 3 | 2.6 ab | 1.7 a | 3.2 ab | 3.1 a | 2.4 ab | 2.5 a |
| 4 | 2.6 ab | 2.0 a | 2.9 ab | 3.3 a | 3.0 a | 2.1 ab |
| 5 | 3.0 a | 2.4 a | 3.8 a | 3.0 a | | |
| Harvest date | | | ** | | | |
| Orchard | * | | * | | * | |

[a] Means with same letter are not significantly different (Fisher's LSD, $P \leq 0.05$).
**, *, significant at $P \leq 0.01$, 0.05, respectively.

Table 2
Kendall Tau-b correlation coefficients between watercore severity and $CO_2$-injury (brown-heart). Fruits harvested 173–188 days after full bloom (DAFB), held 3–12 days at 20 °C in 10 kPa $O_2$+20 kPa $CO_2$ or stored for 4 months at 0.5 °C in 1.5 kPa $O_2$+3 kPa $CO_2$

| Orchard | Harvest date (DAFB) | Days at 20 °C, 10 kPa $O_2$+20 kPa $CO_2$ | | | | 4 month at 0.5 °C, 1.5 kPa $O_2$+3kPa $CO_2$ |
|---|---|---|---|---|---|---|
| | | 3 | 6 | 9 | 12 | |
| 1 | 173 | 0.28 NS | 0.36 NS | 0.56** | 0.51* | 0.83*** |
| | 188 | 0.33 NS | 0.47* | 0.59** | 0.40* | 0.74*** |
| 2 | 173 | 0.16 NS | 0.28 NS | 0.35 NS | 0.24 NS | 0.43 NS |
| | 188 | 0.22 NS | 0.42* | 0.55** | 0.44* | 0.55* |

NS, ***, **, *, Nonsignificant or significant at $P \leq 0.001$, 0.01 or 0.05, respectively.

kPa $O_2 + 20$ kPa $CO_2$, the IEC was much lower than in air-stored fruit and increased continuously with watercore severity. In fruit held 3 days at 20 °C under 10 kPa $O_2 + 20$ kPa $CO_2$ and 4 months at 0.5 °C under 1.5 kPa $O_2 + 3$ kPa $CO_2$, IEC of watercored and watercore-free apples was similar (data not presented). Yet, in fruit held 6 and 12 days at 20 °C in air or 10 kPa $O_2 + 20$ kPa $CO_2$, IEC increased with watercore score similarly to that of fruit exposed 9 days at same temperature and atmosphere (data not presented).

Concentrations of both ethanol and acetaldehyde in the core of 'Fuji' apples consistently increased with severity of watercore regardless of storage condition (Fig. 4). Fruit with severe watercore held 9 days at 20 °C in air accumulated approximately 4 times more ethanol and acetaldehyde than those with no watercore symptoms (Fig. 4A and D). However, apples with severe watercore held 9 days at 20 °C in 10 kPa $O_2 + 20$ kPa $CO_2$ accumulated approximately, three times more ethanol and seven times more acetaldehyde than those with no watercore (Fig. 4B and E). The impact of watercore on ethanol and acetaldehyde production in fruit held 3, 6 and 12 days in air or 10 kPa $O_2 + 20$ kPa $CO_2$ was similar to that in fruit exposed 9 days at the same temperature and atmosphere (data not presented).

## 4. Discussion

The ethane efflux method is a reliable procedure for studies on gas diffusion in bulky plant tissues, particularly in organs such as apple fruit that have a strong surface resistance to gas exchange (Cameron, 1982; Banks, 1985; Rajapakse et al., 1989; Calbo and Nery, 1994). However, dissolved gases in the tissue are a source of error for estimation of $V_g$ by gasometric methods (Calbo and Nery, 1994). The use of tissue cylinders may also introduce error because of flooding of intercellular spaces and new periderm formed at the cut surfaces (Ben-Yehoshua et al. 1963). Using both cylinders and intact fruit, the ethane efflux proceeded linearly during the specified time of equilibration into the efflux jar (data not shown). The results indicate that $V_g$ and $P'_{C_2H_6}$ in watercored apple fruit and tissue cylinders were consistently lower than the same values for watercore-free fruit and tissue cylinders (Fig. 2). This is in agreement with earlier reports showing that flesh resistance to $O_2$ and $CO_2$ diffusion in apples is not negligible and may cause gradients of $CO_2$ and $O_2$ concentration between the surface and the center of fruit (Calbo, 1985; Rajapakse et al., 1989). $P'_{C_2H_6}$ in watercore-free tissue cylinders (Fig. 2C) was approximately, four times higher than that of watercore-free intact whole fruit (Fig. 2A) and

diffusivity of gases in apple flesh can be 10- to 20-fold higher than that of peel (Rajapakse et al., 1989). Tissue cylinders used in the present study were taken along the core line and had approximately half cortex and half pith tissues. In apple fruit, the intercellular space volume of pith is much smaller than that of cortex (Roth, 1977).

The values of $V_g$ ($\approx 20\%$ v/v) for intact watercore-free 'Fuji' apples found in the present study are similar to values for other apple cultivars (Banks, 1985; Rajapakse et al., 1989). Since $V_g$ of flesh can not be differentiated from $V_g$ of the fruit cavity, it is possible that actual values of intercellular air volume for apple flesh are lower than those presented in Fig. 2B. Early-harvested 'Fuji' apples with lower watercore incidence presented at harvest $\approx 18\%$ of air space while those late-harvested with higher watercore incidence presented $\approx 15.5\%$ of air space (Harker et al., 1999). These authors also showed that air space of late-harvested fruit increases to $\approx 20\%$ during same storage period when watercore symptom disappeared.

The resistance to gas movement inside fruit is dependent of intercellular air space volume and continuity (Burg and Burg, 1965; Calbo, 1985). Increased resistance to $CO_2$ and $O_2$ diffusion in post-climacteric avocado flesh is related to the clogging of air spaces by cell exudates (Ben-Yehoshua et al., 1963), and the increase in $O_2$ gradients through the cortex of ripening nectarines is accompanied by decreased intercellular space volume (Rajapakse et al., 1990). Internal concentration profiles for $CO_2$ as a function of the length of fruit radius has been demonstrated for 'Granny Smith' apples (Calbo, 1985). In apples, the diffusivity of $O_2$ varies consistently with the amount of intercellular space volume (Rajapakse et al., 1989). It has been assumed that larger intercellular air space volume generally provides higher diffusivity of gas in fruit tissue, therefore, the reduction of permeance to gases with increased

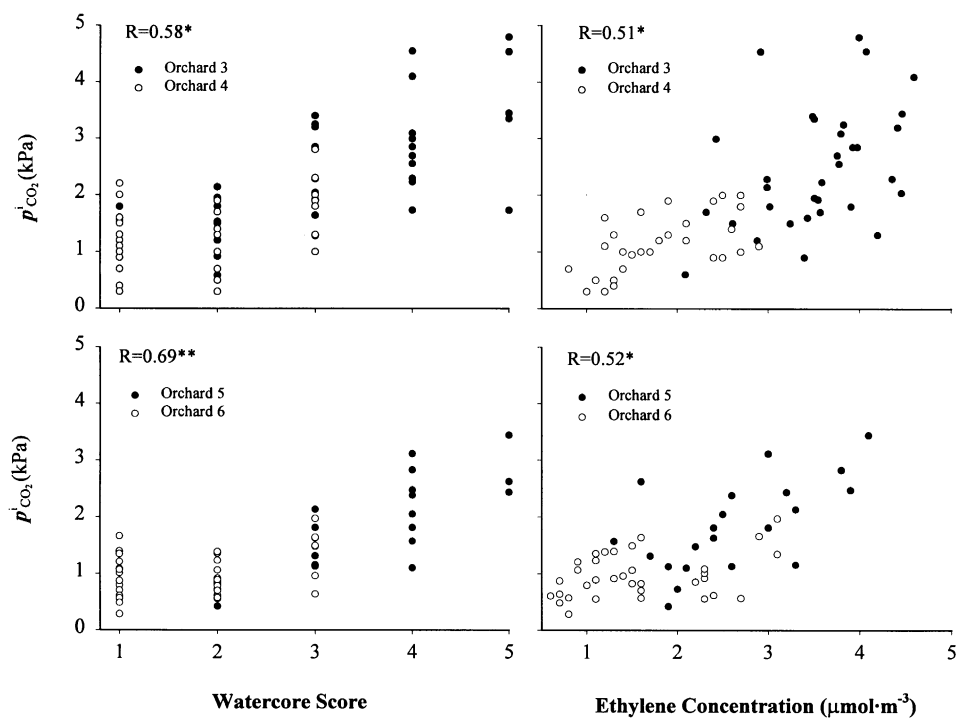


Fig. 1. Internal partial pressure of $CO_2$ ($p^i_{CO_2}$) in 'Fuji' apples as affected by watercore and ripening index (logarithm of internal ethylene concentration) 1 day after harvest. Fruit harvested 192 DAFB from orchards 3 and 4 and 186 DAFB from orchards 5 and 6.

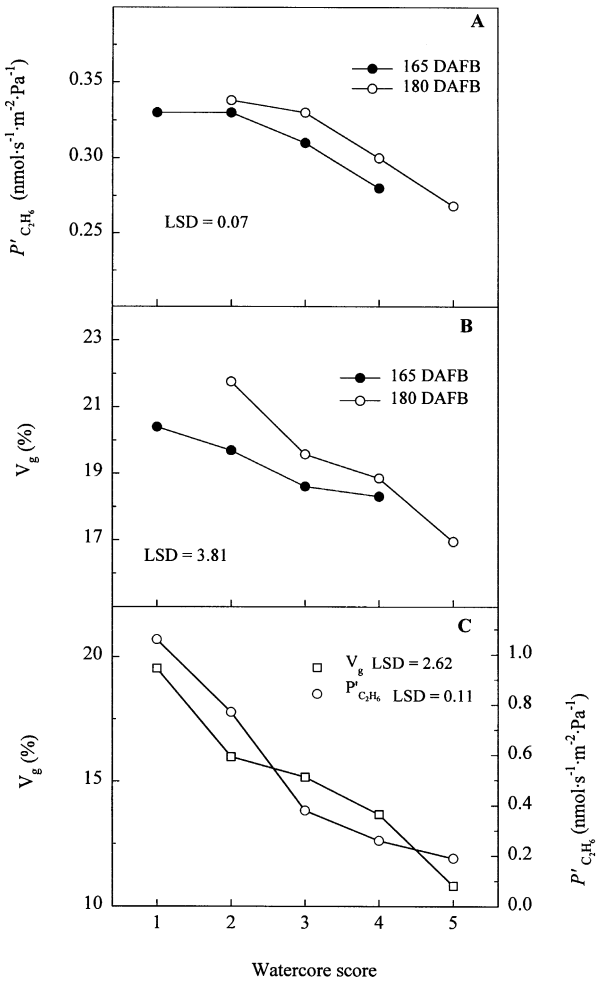


Fig. 2. Relative intercellular air space volume ($V_g$) and permeance to ethane ($P'_{C_2H_6}$) of intact fruit (A and B) and cylinders taken along the core line (C) of 'Fuji' apples as affected by watercore. A and B. Mean values are based on analysis of four to twelve individual apples harvested at 165–180 DAFB from orchard 1. C. Mean values are based on analysis of four 6-cylinders replicates of fruit harvested at 188 DAFB from orchard 1. LSD at $P \leq 0.05$ for significant effect of watercore score on $V_g$ and $P'_{C_2H_6}$ are indicated.

severity of watercore in 'Fuji' apples, could be attributed, at least in part, to the reduction in $V_g$.

Depending on orchard and fruit maturity, an increase in watercore severity may be accompanied by an increase of $p^i_{CO_2}$ (Fig. 1) and decline of $p^i_{O_2}$ (Kato and Sato, 1978). Therefore, increased ethanol and acetaldehyde concentrations (Fig. 4) developing in apples with severe watercore stored in 10 kPa $O_2$ + 20 kPa $CO_2$, may result from low internal $O_2$ and high $CO_2$ concentrations that lead to anaerobic metabolism. The intercellular air space volume, peel porosity and resistance to gas diffusion are factors that determine the occurrence of $CO_2$-injury during storage of apple fruit (Watkins et al., 1997). High resistance to gas diffusion is associated with increased internal $CO_2$-injury (brown-heart) in 'Bramley's Seedling' (Johnson, et al., 1998). Lau (1998) found the highest fruit density in 'Fuji' and 'Braeburn' apples among ten commercial apples cultivars tested. The smallest $P'_{C_2H_6}$ was observed in 'Braeburn' among other apple cultivars (Rajapakse et al., 1989). 'Fuji' and 'Braeburn' apples are considered $CO_2$-intolerant varieties (Kupferman, 1997).

Watercore severity influences ethylene production by 'Fuji' apples. After short-term high $CO_2$ storage (Fig. 3) or at harvest (Bowen and Watkins, 1997) when internal ethylene levels were low, high watercore scores were associated with high IEC. In 'Delicious' apples the production of ethylene is higher and the peak of ethylene production is hastened in watercored fruit compared with watercore-free fruit (Wang and Faust, 1992). As harvest is delayed, watercore severity increases with a corresponding increase in IEC (Kato and Sato, 1978). After short-term air storage, when internal ethylene levels are high, IEC of apples

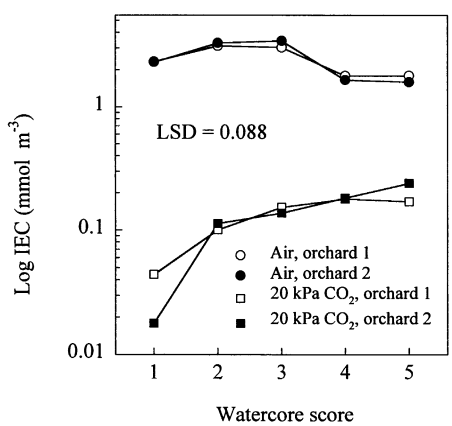


Fig. 3. Internal ethylene concentration in 'Fuji' apples as affected by watercore. Fruit were harvested 188 DAFB in two orchards, then held 9 days at 20 °C in air or in 10 kPa $O_2$ + 20 kPa $CO_2$. Fisher's LSD at $P \leq 0.05$ for significant watercore score x orchard interaction is indicated.

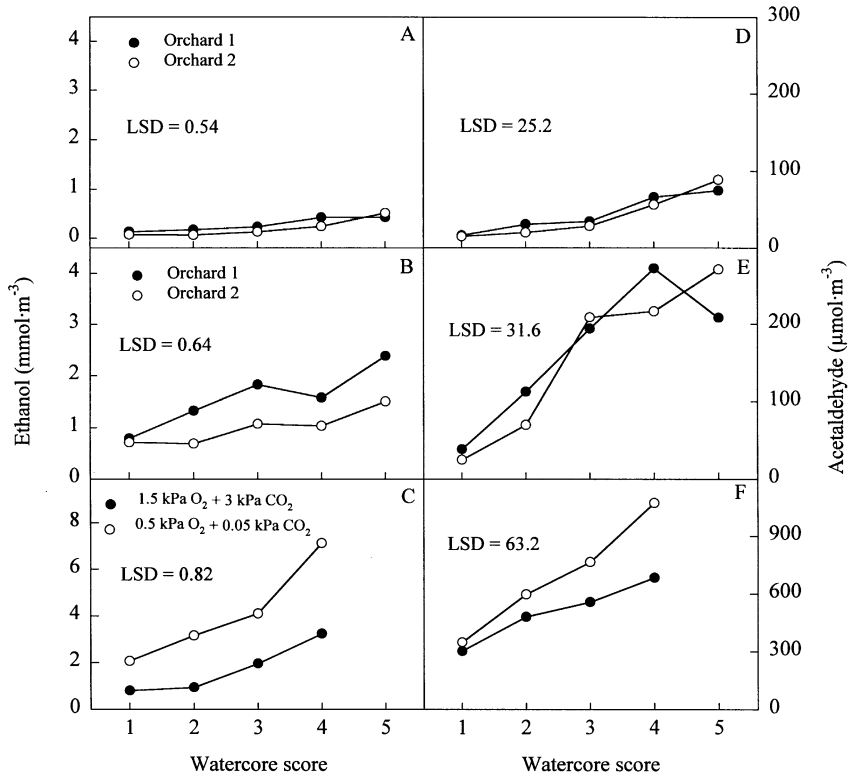


Fig. 4. Internal ethanol and acetaldehyde concentrations in 'Fuji' apples as affected by watercore. A and D. Fruit harvested 188 DAFB, held 9 days at 20 °C in air or B and E. in 10 kPa $O_2 + 20$ kPa $CO_2$. C and F. Fruit harvested 188 DAFB from orchard 1, stored for 4 months at 0.5 °C in 1.5 kPa $O_2 + 3$ kPa $CO_2$ or 0.5 kPa $O_2 + 0.05$ kPa $CO_2$. LSD at $P \leq 0.05$ for significant watercore score x orchard and watercore score x storage treatment interactions are indicated. Legends in A, B and C also apply to D, E and F, respectively.

with low watercore score increased, while IEC decreased in apples with high watercore score compared with watercore-free fruit (Fig. 3). In severely watercored 'Delicious' apples stored longer than nine weeks at 0 °C, the activity of ACC oxidase is inhibited and ethylene production is reduced compared with unaffected fruit (Wang and Faust, 1992). An increase in ethylene production in watercore-affected fruit could be a result of osmotic stress (Wang and Faust, 1992) or an accumulation due the reduction of permeance to ethylene. High $CO_2$ and low $O_2$ reduce ethylene production (Kader, 1986), therefore, a reduction in IEC by very severe watercore could be due to increased $p^i_{CO_2}$ (Fig. 1) and reduced $p^i_{O_2}$ with reduced permeance ($P'_{CO_2}$ and $P'_{O_2}$) caused by very severe watercore.

In conclusion, these results indicate that watercored apple tissue has lower intercellular space volume resulting in a significant reduction of permeance to gas diffusion and increasing $p^i_{CO_2}$ depending on orchard and fruit maturity at harvest. Watercored 'Fuji' apples experience anaerobiosis even at ambient conditions with 21 kPa $O_2$ as indicated by accumulation of ethanol and acetaldehyde. The association between watercore incidence and $CO_2$ injury (brown-heart) at high external $CO_2$ partial pressures may be not simply casual and should be considered during development of commercial CA regimes for 'Fuji' apples.

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